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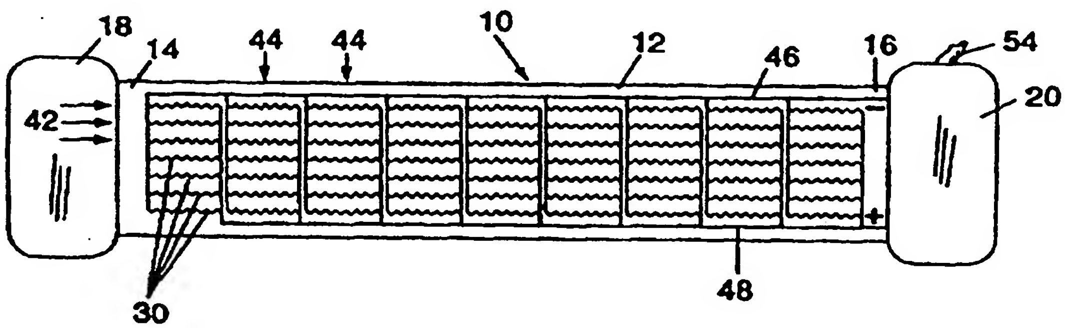
**(54) Title:** ARTIFICIAL MUSCLE




**(57) Abstract**

An artificial muscle cell comprises an elastomeric substrate and an electromagnetic actuator in the form of a coil the turns of which are embedded in the substrate so as to be movable therewith. Enablement of the actuator causes an electromagnetic attraction between the turns of the coil thereby resulting in the contraction of the coil primarily along the longitudinal axis thereof, and the elastomer. An artificial muscle may comprise a single cell or a plurality of cells suitably arranged in a lattice type network, and may be used to operate articulated joints, for example.

# ARTIFICIAL MUSCLE

## FIELD OF INVENTION

This invention relates to an artificial analogue of muscle tissue, otherwise known as artificial muscles. These devices mimic in some measure the actions of naturally occurring muscles, and find use in robotic applications and prostheses, for example.

## BACKGROUND OF INVENTION

Muscle tissue comprises a plurality of muscle fibres which contract under a suitable stimulus. Although the tensile force generated by individual fibres is very small, their cumulative effect can be very high.

It has been contemplated to form artificial muscle using polymer gel fibres that contract in response to changes in the pH of the gel. Microscopic nickel-titanium fibres have also been reported to find use in a similar application. One of the difficulties with both of these types of fibres relates to their relatively slow response time. It does not appear that there has been any commercially viable production of an artificial muscle to the present time.

In US Patent 4,176,411 there is disclosed an artificial muscle-like pump which employs a plurality of electro-magnets embedded in an elastomeric material which is impregnated with ferromagnetic particles. The geometry of the coils of these electro-magnets is fixed, which is to say that upon activation of the electromagnets, the

dimensions of the coils will not change. Such activation engenders the attraction of the ferromagnetic particles, primarily in the radial direction, and the elastomeric substrate therewith, causing it to contract radially. Such radial contraction is to be contrasted with the predominately axial contraction of natural muscle tissue. It will be appreciated that in the absence of the ferromagnetic particles, the enablement of the electromagnets will not result in any contraction of the substrate. The mass of the electromagnets, and of the ferromagnetic particles, together with the relatively large cross-sectional diameter of the structures will tend to make them somewhat inflexible and prone to thermal build-up under heavy duty use.

It is a primary object of my invention to provide artificial muscle structures which mimic the action of muscle tissue.

It is another object of my invention to provide artificial muscle that may be light weight and formed in thin sections.

It is still another object of my invention to provide artificial muscle that is relatively flexible.

It is yet another object of my invention to provide artificial muscle which permits a more efficient heat dissipation.

It is another object of my invention to provide artificial muscle wherein the response time can be easily controlled.

It is yet another object of my invention to provide artificial muscle wherein the response time can be controlled so as to be variable between very rapid and slow.

It is still another object of my invention to provide artificial muscle wherein the muscular force can be easily varied and controlled.

SUMMARY OF INVENTION

In accordance with one aspect of my invention, an artificial muscle comprises an elastomeric substrate extending in at least two dimensions, and an electromagnetic actuator comprising a coil having a longitudinal axis wherein the turns of the coil are embedded in the substrate in a manner whereby enablement of the actuator serves to create an electromagnetic attraction between the turns, serving to decrease the dimension of the wire coil along its longitudinal axis, and the substrate therewith, and thereby cause the muscle cell to contract in a manner that is similar to that of natural muscle tissue.

The wire coils are essentially open, and may be wound so as to be relatively flat, whereby thin, flexible artificial muscle structures from which heat is readily dissipated can be fabricated.

The magneto-constrictive action of the muscle cells of the invention does not necessitate or require the presence of any ferromagnetic particles in the substrate, and accordingly the muscle cells of the invention may be formed with a density comparable to that of natural muscle tissue.

The indication that the substrate extends in two dimensions is not meant to infer that the substrate extends in two dimensions only. The artificial muscles of the invention have a length, width and thickness, and in accordance with the preferred embodiment the dimension of the artificial muscles in the thickness is preferably appreciably less than that in the length and width. Moreover, although the enablement of the actuator will preferably act to change the length of the muscle, change may also be experienced in the width and thickness.

Preferably, the substrate is impregnated with a substance to increase the magnetic permeability thereof, suitably with ferromagnetic particles.

In accordance with the preferred embodiment, the actuator is embedded in the substrate by molding. However, it will be understood that other means linking the substrate to the actuators may also be employed as convenient.

It will be appreciated that merely by controlling the current supplied to an actuator, both the speed of response of the actuator and the forces generated thereby can be varied, and that the response time may be very rapid if desired. In addition, the effectiveness of the magnetic interaction of the electromagnetic field generated by the actuator may be varied to vary the basic characteristics of the artificial muscle. Still other ways of changing the characteristics of the muscle may occur to those skilled in the art.

The elastomeric material of the substrate includes natural and synthetic rubbers and rubber-like materials having a modulus of elasticity that will be appropriate for the intended use of the artificial muscle.

The electromagnetic actuator in a preferred form comprises a wire coil which has in transverse cross section a major axis and a minor axis, wherein the dimension on the minor axis is substantially less than that of the major axis, commensurate with the desired thickness of the muscle.

Each actuator and associated substrate forms a muscle cell, and a muscle may comprise a single cell or a plurality of such cells. Where a plurality of cells are employed, these may conveniently be in the form of a generally two dimensional lattice, and the actuators may be connected in parallel relationship or otherwise, as desired. Composite muscle structures may also be formed from groups of muscle cells.

The muscles of the invention will find a wide range of applications, including without limitation, the actuation of joints, which may be articulated in a similar manner to those of animal skeletons, constricting sleeves for use as casts, and peristaltic pumps. Moreover, it will be appreciated that the muscle cells of the invention are simple motors, and they may find other uses than those suggested above.

Typically and preferably, the artificial muscle will be held with the substrate under tension, and enablement of the actuator or actuators will serve to increase the tension of the muscle at its anchor points by decreasing the tension of the substrate between the anchor points. However, other forms of operation may also be used.

The foregoing objects and aspects of the invention, together with other objects, aspects and advantages thereof will be more apparent from a consideration of the following description of the preferred embodiment thereof taken in conjunction with the drawings annexed hereto.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings,

**Fig. 1** shows in highly schematic form an artificial muscle formed as a lattice of muscle cells of the invention, in plan form;

**Fig. 2** shows the muscle of Fig. 1 in side elevation;

**Fig. 3** shows on enlarged scale three component elements of the muscle of Fig. 1;

**Fig. 4** is similar to Fig. 3, but shows the elements in contracted form;

**Fig. 5** shows in perspective view one of the elements of Fig. 3 in greater detail, broken to show indefinite length;

**Fig. 6** is a cross-section on line 6 - 6 of Fig. 5, together with surrounding structure;

**Fig. 7** is similar to Fig. 6, but shows the muscle in contracted form;

**Fig. 8** shows a composite embodiment of an artificial muscle of the invention; and

**Fig. 9** shows a composite embodiment of another artificial muscle arrangement of the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the drawings in detail, an artificial muscle is identified generally therein by the numeral 10. Muscle 10 comprises a thin elastomeric substrate 12 having longitudinally opposed ends 14, 16, terminated by anchors 18, 20 by which muscle 10 may be secured to an artificial joint. A plurality of electromagnetic actuators 30 are embedded in substrate 12. Each actuator 30 comprises a coil 32 of conductor wire; as best seen in Fig. 6, the coils in cross-section have a major axis 34 and a minor axis 36, with the dimension along the minor axis being substantially less than that along the major axis so as to have a low aspect ratio consistent with the desired thickness of muscle 10. Coils 32 have a longitudinal axis 38, the axis of each of the coils being parallel. In effect the coils 32 are arranged to form a two dimensional lattice of actuators 30 arranged in rows 42 and columns 44. A pair of electrical buses 46, 48 extends along the length of substrate 12. The longitudinally opposed ends of coils 32 of each row 44 of the coils are respectively connected to buses 46 and 48 by yokes 50, 52 so as to be in electrical parallelism, the yokes also serving to anchor the coils within substrate 12. An enabling electromotive force is conveniently applied to busses 46, 48 through conductor 54, causing an electromagnetic contraction of coils 32, as will be further described. Such

contractive force is enhanced by impregnating substrate 12 with ferromagnetic particles 58.

In use, muscle 10 will normally be anchored through anchors 18, 20 so as to place substrate 12 under tension. A suitable electromotive force applied to buses 46, 48 will then cause the electromagnetic actuators 30 to contract under the influence of the electromagnetic field. The primary contraction will be along the longitudinal axis of coils 32, as suggested by arrows 56 in Fig. 4. However, coils 32 will also tend to assume a circular form, whereby the cross sectional shape of the muscle 10 will move towards that depicted in Fig. 7. This contraction in the transverse plane will tend to contract the muscle 10 in the longitudinal plane; it will also have the effect of increasing the contractile force that may be generated for a given length of muscle cell. The rate and degree of contraction generated are easily regulated by controlling the electromotive force applied to buses 46, 48, and suitably a feedback circuit (not shown) will be used to control the operation of muscle 10, as is generally known in the art.

It will be appreciated that each electromagnetic actuator 30, together with the supporting portion of substrate 12, forms an artificial muscle cell 80. Within reason, there is no limit to the physical dimensions of a muscle cell 80, of the number of such cells that may be employed to form a composite muscle such as muscle 10, and of their manner of deployment. Thus, where more than one muscle cell is employed, the cells may be connected so as to be individually operated or operated in groups, as may be desired for any particular purpose. Accordingly, the artificial muscles of the invention may be embodied in widely different forms. One such form is suggested in Fig. 8, wherein an artificial muscle 110 comprises three muscle cells 80 arranged in a striated

manner. In Fig. 9, a composite artificial muscle 210 is built up from three groups A,B & C of muscles 10, with each group being operative independently of any other group. Numerous other arrangements will occur to persons in the art according to the desired function of the artificial muscle.

CLAIMS

1. An artificial muscle cell comprising an elastomeric substrate extending in at least two dimensions, and an electromagnetic actuator therefor characterized wherein said actuator comprises a wire coil having a longitudinal axis embedded in said substrate in a manner whereby enablement of said actuator serves to decrease the dimension of said wire coil along said longitudinal axis and thereby cause said muscle cell to contract.

2. An artificial muscle cell as defined in Claim 1 wherein said elastomeric substrate is impregnated with a substance to increase the magnetic permeability thereof.

3. An artificial muscle cell as defined in Claim 2 wherein said substance comprises ferromagnetic particles.

4. An artificial muscle cell as defined in Claim 1, 2 or 3 wherein said wire coil has in transverse cross section a major axis and a minor axis, and the dimension on the minor axis is substantially less than that on said major axis.

5. An artificial muscle cell as defined in Claim 4 wherein said wire coil has a length, and terminates at ends opposed by said length, and wherein each said end is secured to a yoke.

6. An artificial muscle comprising a plurality of muscle cells as defined in any one of claims 1-5.

7. An artificial muscle as defined in Claim 6 wherein said plurality of muscle cells are formed in a two dimensional lattice.

8. An artificial muscle as defined in Claim 6 wherein said plurality of muscle cells are electrically connected in parallel relationship.

Fig 1

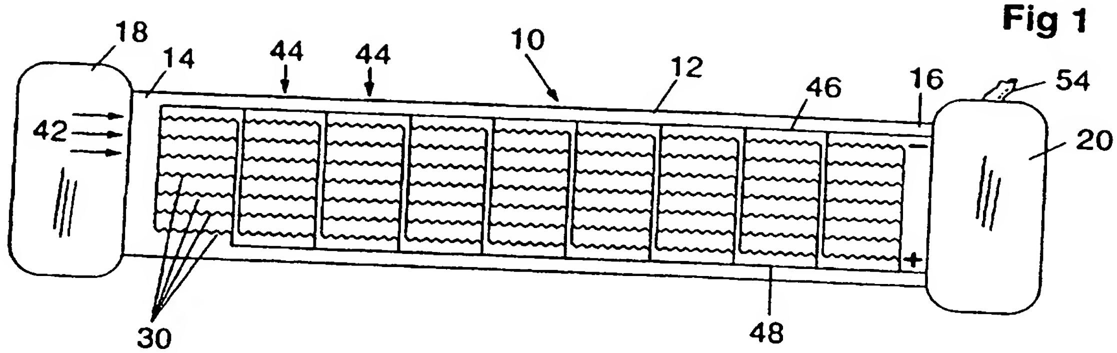



Fig 2

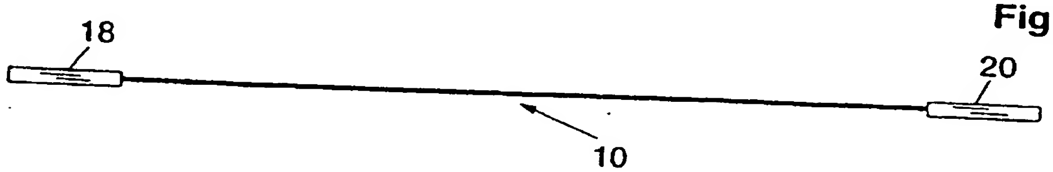



Fig 3

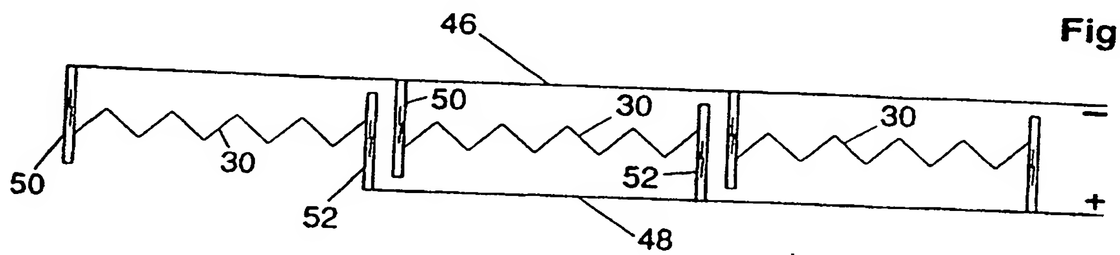



Fig 4

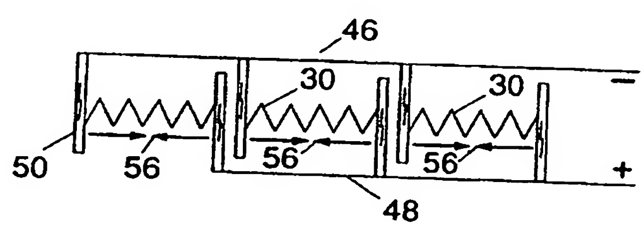
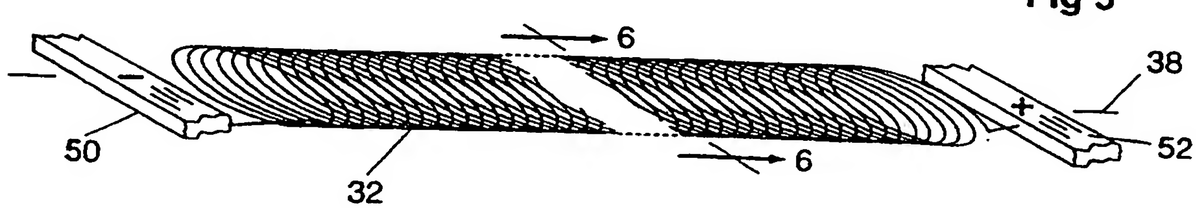



Fig 5



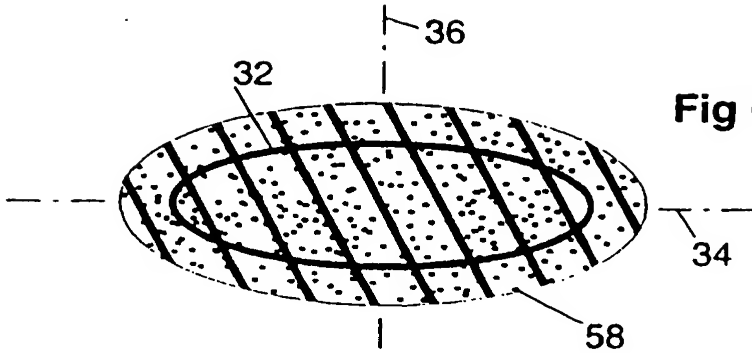



Fig 6

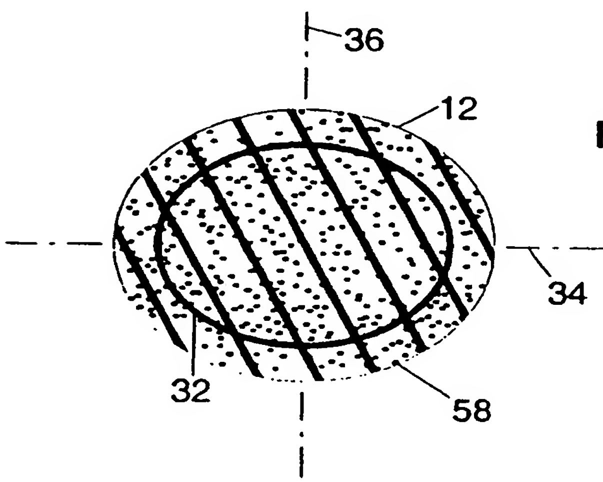



Fig 7

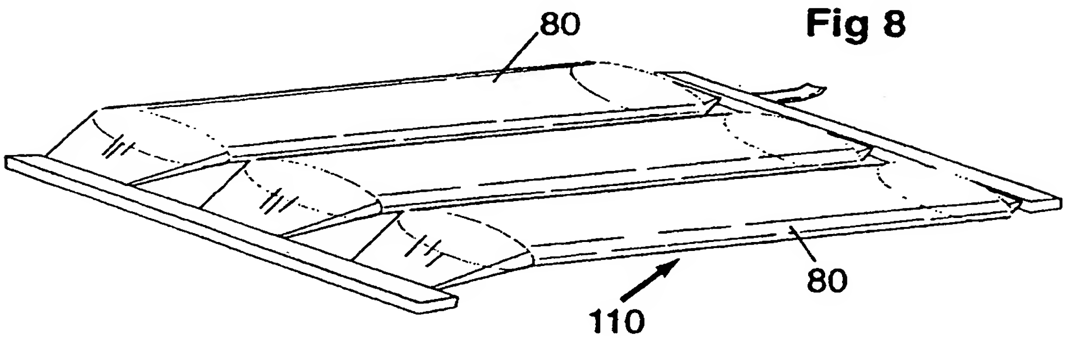



Fig 8

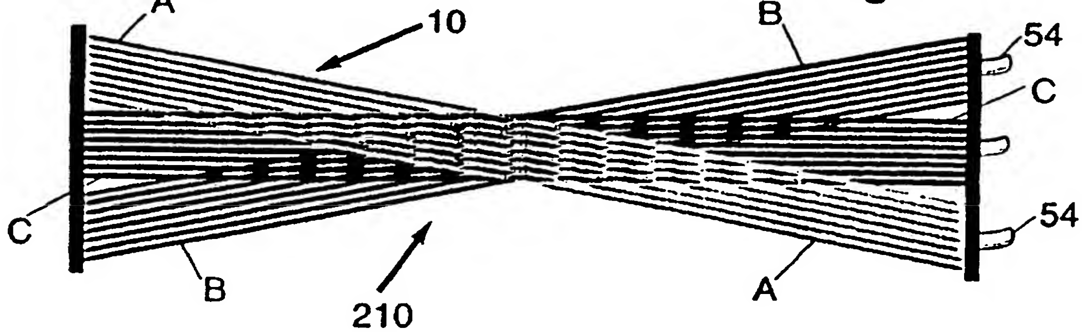



Fig 9

# INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00061

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 6 A61F2/08 B25J9/10 A61F2/68 H01F7/06

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61F B25J H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | FR 2 591 928 A (LORIN DE LA GRANDMAISON) 26 June 1987<br>see page 6, line 14 - line 20; claim 1; figures | 1-8 |
| Y | US 4 176 411 A (RUNGE) 4 December 1979<br>cited in the application<br>see the whole document | 1-8 |
| A | EP 0 628 385 A (DAUM) 14 December 1994<br>see column 6, line 20 - line 28; figures<br>see column 5, line 31 - line 37 | 1 |
| A | US 5 062 855 A (RINCOE) 5 November 1991 | |
| A | US 3 201 729 A (BLANCHI) 17 August 1965 | |
| A | US 5 250 167 A (ADOLF) 5 October 1993 | |

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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"&" document member of the same patent family

1

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 15 April 1997 | 29.04.97 |

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International Application No
PCT/CA 97/00061

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| US 3201729 A | 17-08-65 | NONE | |
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